

Output Gaps and Monetary Policy at Low Interest Rates

By Roberto M. Billi

Policymakers use various indicators of economic activity to assess economic conditions and set an appropriate stance for monetary policy. A key challenge for policymakers is finding indicators that give a clear and accurate signal of the state of the economy in real time—that is, at the time policy is actually made. Unfortunately, most indicators are initially estimated based on incomplete information and subsequently revised as more information becomes available. Moreover, some indicators are based on economic concepts that are not directly observable.

Two indicators of economic activity often used to guide monetary policy are the output gap and the growth rate of real GDP. The output gap measures how far the economy is from its full employment or “potential” level. The output gap is a noisy signal of economic activity, however, because it depends on potential GDP, which is unobservable, and because it depends on estimates of GDP that are subject to revision. In contrast, estimates of GDP growth have the advantage of being observable—albeit with a lag. But these estimates are also subject to revision as more and better underlying information becomes available.

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Given the possibility that either of the indicators could give an inaccurate signal in real time, should one indicator be favored over the other as a guide for policy? This article uses a standard model to compare economic performance under a policy that focuses on the output gap with one that focuses on GDP growth. A novel feature of the analysis is that it takes account of the zero lower bound (ZLB) on nominal interest rates. Previous research ignored the ZLB and implicitly allowed policymakers to set policy rates below zero.

The article concludes that policymakers should usually focus on the output gap as an indicator of economic activity when policy rates are constrained by the ZLB. A policy that focuses on GDP growth can lead to more frequent encounters with the ZLB, which, in turn, lead to more volatility in output and inflation. In failing to account for the ZLB, previous research overstated the effectiveness of a policy that focuses on GDP growth.

The first section of the article describes the challenges associated with using the output gap and GDP growth to guide monetary policy. The second section compares economic performance under such policies in the absence of the ZLB. The analysis in the third section takes account of the ZLB.

I. MEASUREMENT CHALLENGES AND IMPLICATIONS FOR POLICY

In monetary policy analysis, two commonly used measures of economic activity are the output gap and real GDP growth. While the output gap is conceptually appealing as an indicator to help guide policy, real GDP growth is measured in real time with greater accuracy. Recognizing this tradeoff, researchers have examined the use of both indicators in simple rules for monetary policy.

The output gap and GDP growth

The output gap is a gauge of how far the economy is from its productive potential. Potential output is determined by supply-side factors, such as the supply of workers and their productivity. Over the business cycle, because aggregate demand may exceed or fall short of aggregate supply, GDP may rise above or fall below potential. A typical story is that during a boom, the economy rises above its productive

potential and the output gap is positive. During a recession, the economy falls below its productive potential and the output gap is negative.

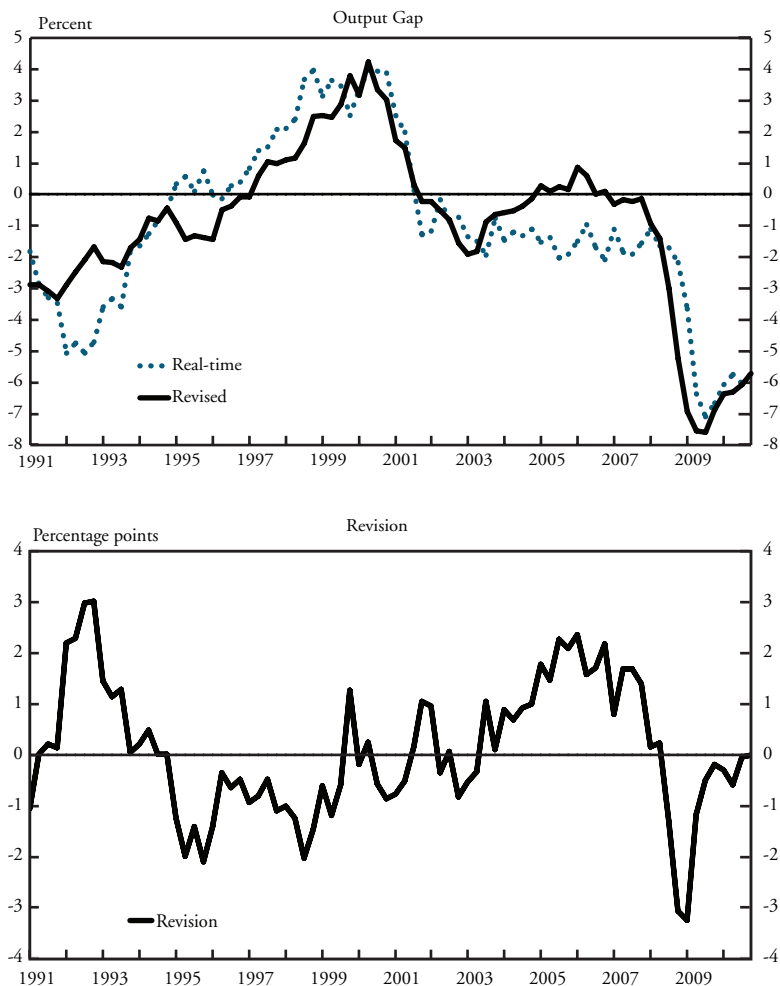
The output gap is conceptually appealing because it is an important determinant of inflation developments. A positive output gap implies an overheating economy and upward pressure on inflation. By contrast, a negative output gap implies a slack economy and downward pressure on inflation. Thus, if available, accurate and timely measures of the output gap can play a central role in the conduct of effective monetary policy. A positive output gap might prompt policymakers to cool an overheating economy by raising policy rates, while a negative output gap might prompt monetary stimulus.

In practice, however, measuring the output gap involves two complications. First, potential output cannot be measured directly and therefore must be estimated.¹ Second, GDP data are regularly revised as government statistical agencies incorporate more complete source information and new methodologies into the published data. The revised data may differ significantly from the initial release. Research has shown that estimating potential output is the main source of errors in measuring the output gap (Orphanides and van Norden). A prominent example is the Great Inflation of the 1970s. During the period, many believed the economy's productive potential to be higher than it actually was.² This misperception may have contributed to an inflationary bias to policy to the extent that policymakers reacted to the mismeasured output gap (Orphanides, 2003b).

In recent decades as well, the accuracy of estimates of the output gap has been questionable. To illustrate, Chart 1 shows the Congressional Budget Office (CBO) estimates from 1991 to 2010. The top panel shows two series. One series is *real-time* estimates (dashed line), which reflect information available to policymakers at the time decisions were actually made.³ The other series is the most recently *revised* estimates (solid line), which reflect information available today with the benefit of hindsight. As is evident in the chart, the revised and real-time estimates often lie far apart.

From 1991 to 2010, the revisions to the real-time output gap estimates were relatively large. The difference between the real-time estimates and the most recent estimates of the output gap ranged from -3.3 to 3.0 percentage points (lower panel in Chart 1). Moreover, full percent-

Chart 1

OUTPUT GAP BASED ON REAL-TIME AND
REVISED DATA

Notes: The period is 1991:Q1 to 2010:Q4. The output gap is calculated as the deviation of real GDP from potential, as a fraction of potential using seasonally adjusted data. Real-time data reflect information actually available each quarter. Revised data reflect information available in January 2011. The revision is the difference between the revised and real-time series.

Sources: Bureau of Economic Analysis (real GDP), Congressional Budget Office (potential), and author's calculations

age-point revisions were common. The mean absolute revision was 1.1 percentage points. The persistence of the revisions was also considerable.

Recognizing such errors in measuring the output gap, some policymakers instead favor the growth rate of real GDP to help guide policy (Plosser). Since GDP growth only depends on directly observed output data, this measure is not prone to errors from estimating potential output.

Estimates of real GDP growth, however, are subject to revision. For example, from 1991 to 2010, the revisions to the real-time GDP growth estimates ranged from -2.6 to 1.8 percentage points (top panel in Chart 2).⁴ Also notable was the persistence of the revisions to GDP growth, which was similar to that of the revisions to CBO's output gap (Chart 3).⁵ Still, the mean absolute revision for GDP growth was only 0.6 percentage point, slightly more than half that for CBO's output gap. In short, revisions to GDP growth are typically smaller than revisions to the output gap.

Implications for policy rate decisions

Errors in measuring economic activity may lead to policy regret. In other words, at times the revised data may suggest that alternative actions would have been preferable to those actually taken using real-time data.

To gain insight into the implications of mismeasurement in policy decisions, the setting of the policy rate can be characterized by two simple policy rules. The *Taylor rule* relates the policy rate to inflation and the output gap. A modified version of the Taylor rule, or a *growth rule*, relates the policy rate to inflation and GDP growth. In this analysis, both the output gap and GDP growth are assumed to be measured in real time with errors.⁶

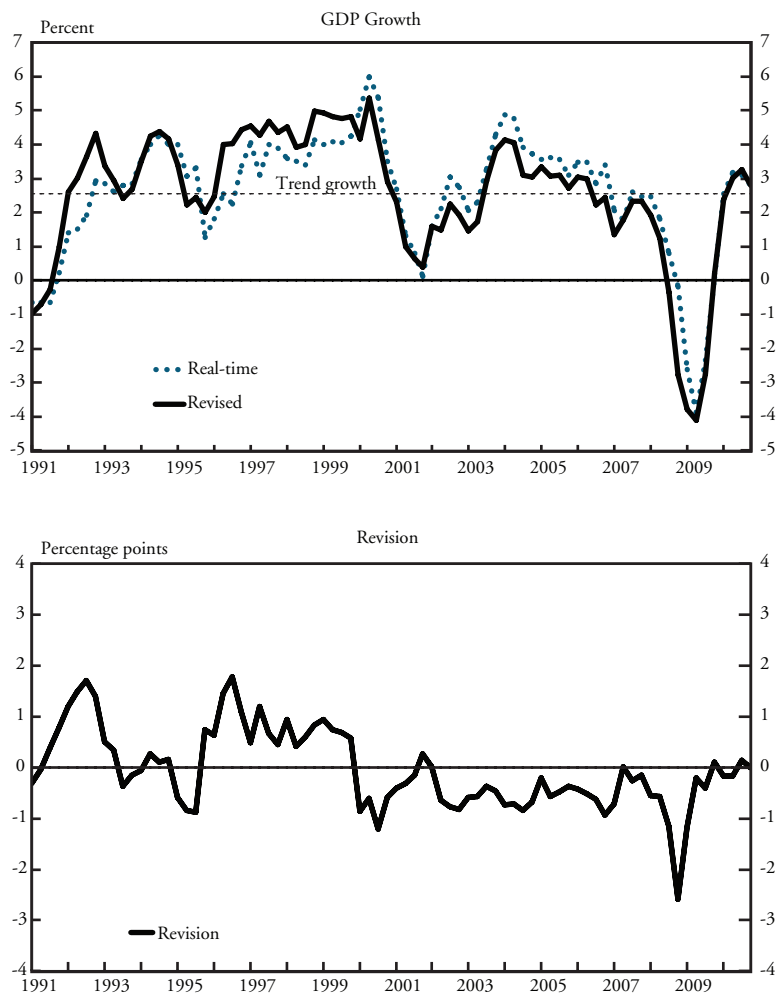
The Taylor rule takes the following form:

$$i_t = i^* + \alpha(\pi_t - \pi^*) + \gamma(\tilde{y}_t - \tilde{y}_t^*). \quad (\text{TR})$$

On the left side of this rule, i_t represents the prescribed level of the policy rate in a given period. The policy rate is expected to be zero or positive because, under normal circumstances, nominal interest rates cannot fall below zero.⁷ Past research, however, has often ignored the ZLB and implicitly allowed the policy rate to fall below zero.

Chart 2

REAL GDP GROWTH BASED ON REAL-TIME AND REVISED DATA

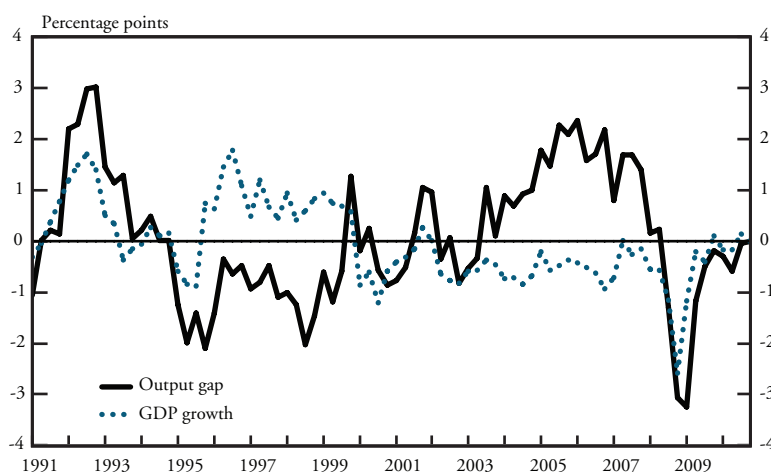


Notes: The period is 1991:Q1 to 2010:Q4. Real GDP growth is calculated as the four-quarter change in real GDP using seasonally adjusted data. Trend growth is average growth over the post-1990 period shown. Real-time data reflect information actually available each quarter. Revised data reflect information available in January 2011. The revision is the difference between the revised and real-time series.

Sources: Bureau of Economic Analysis (real GDP) and author's calculations

Chart 3

REVISION TO OUTPUT GAP AND GDP GROWTH



Notes: The period is 1991:Q1 to 2010:Q4. The revision is the difference between the revised and real-time series, for each of the output gap (Chart 1) and GDP growth (Chart 2).

Source: Author's calculations

On the right side of the rule, three factors influence the prescription for the policy rate. The first factor is the *equilibrium nominal rate of interest*, or the equilibrium real rate plus policymakers' long-run inflation goal ($i^* = r^* + \pi^*$).⁸ The second factor is the *inflation gap*, or the deviation of current inflation from the inflation goal ($\pi_t - \pi^*$). And the third factor is the real-time *output gap*, or the deviation of real GDP from potential ($\tilde{y}_t - \tilde{y}_t^*$).

The Taylor rule prescribes that policymakers set the policy rate equal to the equilibrium nominal rate when the inflation and output gaps are at zero. When the gaps deviate from zero, however, dampening fluctuations of inflation and output requires coefficients α and γ be positive.⁹ Thus, for example, policymakers using the rule will ease policy by lowering the policy rate when inflation falls below the goal or GDP falls below potential. Conversely, policymakers will tighten policy by raising the policy rate when inflation rises above the goal or GDP rises above potential.

To use the Taylor rule, policymakers must estimate the output gap in real time with preliminary data on the current level of GDP. Any

errors from estimating potential GDP or inaccurate data on current GDP will lead policymakers to set the policy rate inappropriately. As a consequence, the policy rate will differ from what would otherwise be the prescription based on the later revised output gap estimate—an instance of policy regret. Further, “misguided” changes in policy rates may adversely affect the economy. For example, policymakers might ease policy and fuel inflationary pressures as they react to real-time indicators of a fall in output below potential, only to discover later the indicators were inaccurate.

An alternative strategy is to ignore the output gap altogether and focus on real GDP growth, using a growth rate rule.¹⁰ Such a growth rule takes the form:

$$i_t = i^* + \delta(\pi_t - \pi^*) + \theta(\tilde{g}_t - g^*). \quad (\text{GR})$$

On the right side of this rule, the first two factors are the same as in the Taylor rule. The third factor, however, is the real-time *growth gap*, or the deviation of real GDP growth from trend ($\tilde{g}_t - g^*$), instead of the output gap. In this analysis trend growth is measured by average growth over a long period.¹¹

Dampening fluctuations of output requires the coefficient θ be positive. Thus, for example, policymakers using the rule will ease policy by lowering the policy rate when real GDP growth falls below trend. Conversely, policymakers will tighten policy by raising the policy rate when real GDP growth rises above trend. Inaccurate estimates of GDP growth, of course, will lead policymakers to set the policy rate inappropriately.

Nevertheless, it is not clear which indicator of economic activity is less likely to lead to policy regret. While the output gap may be the better conceptual indicator, revisions may be smaller for real GDP growth. The effectiveness of these two indicators as policy guides can be compared using a model of the economy.

II. POLICY EVALUATION IN THE ABSENCE OF THE ZERO BOUND

As discussed in the previous section, the output gap is an important concept in monetary policy analysis—but the accuracy with which it is measured is suspect. An alternative indicator of economic activity is GDP growth. This section uses a standard model to compare economic performance under policies that focus on these two indicators. As in

previous research, the analysis ignores the ZLB. The section describes the key features of the model (the technical details are available in the Appendix). It then presents evidence that, when using real-time data, a policy that focuses on GDP growth can lead to less volatility in output and inflation than a policy that focuses on the output gap.

Key features of the model

The standard model—a basic version of the New-Keynesian model—explains in simple terms the behavior of households, firms, and a central bank. Households decide how much they wish to work, purchase goods, and save. Firms decide how much labor to hire and how to price their goods. Moreover, as typical in macro models, the output gap is a key determinant of the behavior of the private sector and of inflation developments. For example, households work less and firms lower prices when GDP falls below potential. Conversely, households work more and firms raise prices when GDP rises above potential. In determining the policy rate, the central bank follows either the Taylor rule or the growth rule.

The specification of the Taylor rule generally follows Taylor's (1993) proposal. Both the equilibrium real rate and policymakers' long-run inflation goal are assumed to be 2 percent annually. The coefficients on the inflation gap and the output gap are 1.5 and 0.5, respectively. In addition, the output gap is measured as the deviation of real GDP from its noninflationary rate—determined by the microeconomic foundations of the model—as opposed to the deviation of real GDP from an estimate of its trend growth as in Taylor's proposal. As a result, the measure of the output gap used in this analysis is closely related to CBO's measure (Kiley).¹² Finally, inflation is measured by the GDP deflator.

The growth rule is specified similarly. To make the rules comparable, however, the coefficient on the inflation gap in the growth rule is chosen to produce the same output gap volatility under both rules in the absence of the ZLB and measurement error.¹³ In addition, trend growth is assumed to be 2.5 percent annually, reflecting average growth from 1991 to 2010.

Finally, measurement errors must be specified for each indicator of economic activity in the policy rules.¹⁴ This analysis considers a case with measurement errors of *normal* size, in which the errors are assumed to have the same standard deviation as the historical revisions

from 1991 to 2010 (Chart 3).¹⁵ Specifically, the measurement error in the Taylor rule was taken from the revisions to CBO's real-time output gap estimates, while the measurement error in the growth rule was taken from the revisions to the real-time GDP growth estimates. As a result, reflecting the relative size of the historical revisions, the measurement errors were chosen to be generally smaller for GDP growth. Since the size of the revisions going forward is an open question, the analysis also considers a case with *large* measurement errors, in which the errors are assumed to have a standard deviation 50 percent larger than the historical revisions.

In the standard model—and in most macro models used for monetary policy analysis—a policy that focuses on the output gap would be expected to be more-effective when economic activity is assumed to be measured accurately in real time. Such a policy is more effective because the output gap is a key determinant of the behavior of the private sector and therefore inflation.

When measurement errors are taken into account, however, a more effective policy may be to focus on real GDP growth. Such a policy may be more effective because GDP growth is measured in real time with greater accuracy than the output gap. As a result, if the real-time output gap estimates are unreliable, a policy that focuses on GDP growth may lead to less volatility in output and inflation.

Evidence from the model

The volatility in output and inflation associated with each policy depends on the size of the measurement errors. Table 1 shows how the model economy performs under both the Taylor rule and the growth rule as the extent of the measurement errors is varied. As in previous research, the analysis ignores the ZLB. Each row shows the volatility or standard deviation of inflation and the real output gap for a different size of measurement error—none, normal, and large. Also shown is the percent increase in volatility due to measurement error.

The table shows the following results:

1. Without measurement errors, the Taylor rule leads to less volatility in inflation than the growth rule—and the same volatility in the output gap.
2. With measurement errors, volatility rises under both rules. However, it rises by less under the growth rule.¹⁶

Table 1

ECONOMIC PERFORMANCE IN THE ABSENCE OF THE ZLB

<i>Taylor Rule</i>				
Measurement errors:	Standard deviation (Percent increase)			
	Inflation		Real output gap	
None	0.34		1.08	
Normal	0.54	(59)	1.38	(28)
Large	0.71	(109)	1.68	(56)
<i>Growth rule</i>				
Measurement errors:	Standard deviation (Percent increase)			
	Inflation		Real output gap	
None	0.42		1.08	
Normal	0.47	(12)	1.16	(7)
Large	0.53	(26)	1.24	(15)

Notes: Shown is the standard deviation in annualized percentage points obtained from a standard model calibrated to the U.S. economy (Appendix). Bold font indicates under which policy rule the standard deviation is lower. The output gap and GDP growth are assumed to be measured in real time with errors. Three cases for the measurement errors are considered: none (no errors), normal (errors with the same standard deviation as the historical revisions) and large (errors with standard deviation 50 percent larger than the historical revisions). Shown in parenthesis is the percent increase of the standard deviation relative to the no-errors case.

Source: Author's calculations

3. With normal measurement errors, under the Taylor rule the volatility of inflation rises 59 percent and the volatility of the output gap rises 28 percent. In contrast, under the growth rule volatility rises only 12 percent for inflation and 7 percent for the output gap. Thus, volatility is lower under the growth rule than under the Taylor rule.
4. With large measurement errors, under the Taylor rule the volatility of inflation rises 109 percent and the volatility of the output gap rises 56 percent. In contrast, under the growth rule volatility rises only 26 percent for inflation and 15 percent for the output gap. Thus, volatility is lower under the growth rule than under the Taylor rule.

As a result, if the analysis takes account of errors in measuring economic activity, the growth rule can lead to less volatility in output and inflation. A number of recent studies, using a variety of models, reach similar conclusions (Orphanides, 2003a; Orphanides and others; Orphanides and Williams; Smets; Taylor and Williams; Walsh). The bottom line is that a policy that ignores the output gap and focuses on real

GDP growth can lead to less volatility in output and inflation to the extent that real GDP growth gives a more-accurate signal of economic activity in real time than the output gap.

III. POLICY EVALUATION IN THE PRESENCE OF THE ZERO BOUND

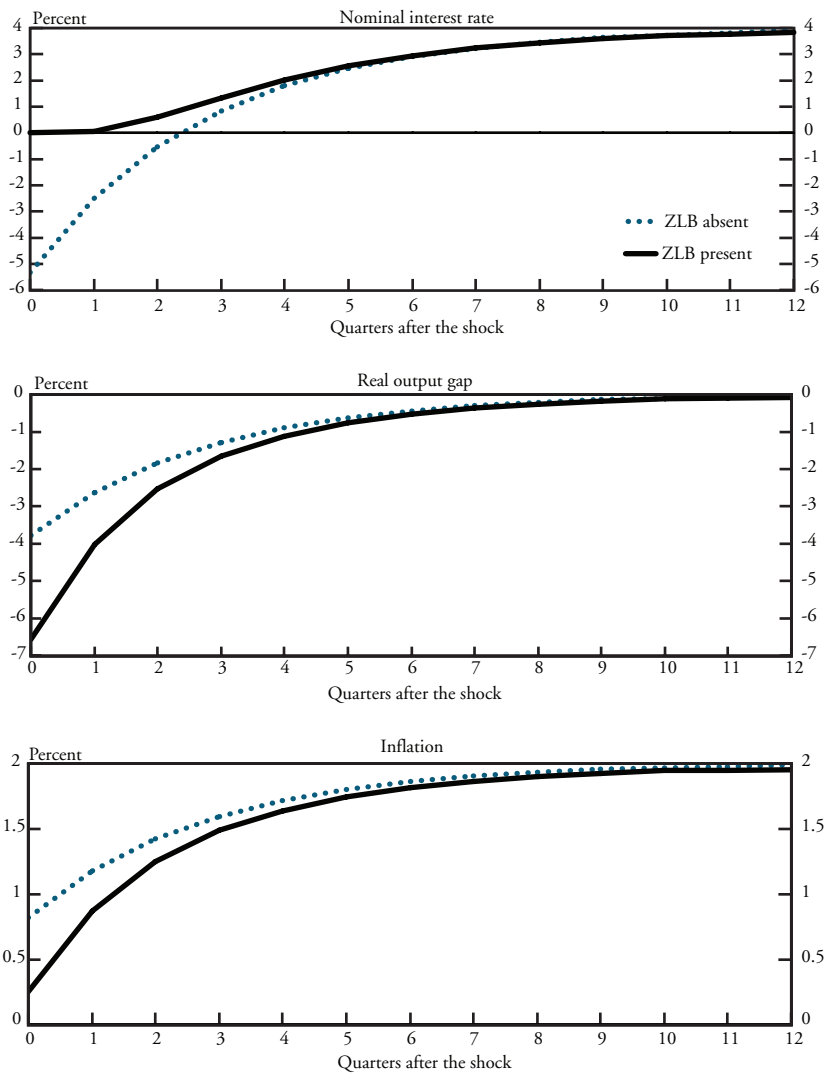
Previous studies have compared economic performance under policies that focus on the output gap versus real GDP growth. But the studies have ignored the ZLB by implicitly—and unrealistically—allowing policy rates to fall below zero. While a policy that focuses on GDP growth may be more robust to errors in the measurement of economic activity, it may lead to a higher incidence of hitting the ZLB. In failing to recognize this tradeoff, past research has overstated the effectiveness of a policy that focuses on GDP growth.

Focusing on GDP growth may force policymakers to move the policy rate more vigorously to offset disturbances to aggregate demand, resulting in more frequent encounters with the ZLB.¹⁷ A higher incidence of hitting the ZLB leads to a greater volatility in output and inflation. As a result, when policy rates are constrained by the ZLB, a policy that focuses on GDP growth may become less effective.

Irrespective of measurement errors, the ZLB constrains the central bank's ability to lower the policy rate and stimulate the economy during downturns. This inability to reduce the policy rate below zero may impair the effectiveness of monetary policy to stabilize output and inflation. To illustrate, Chart 4 shows the dynamics of the model economy following an adverse shock to aggregate demand.¹⁸ In the top panel, the solid line shows that the central bank, using the Taylor rule, lowers the policy rate to zero in the presence of the ZLB. The dashed line shows that the central bank would further cut the policy rate to -5.3 percent in the absence of the ZLB. The sizeable shortfall of monetary stimulus due to the ZLB leads to a sharper economic downturn (middle and bottom panels). In the absence of the ZLB, real GDP falls 3.8 percent below potential and inflation falls to 0.8 percent. In the presence of the ZLB, real GDP falls 6.6 percent below potential and inflation falls to 0.3 percent.

Chart 4

ECONOMIC DYNAMICS FOLLOWING AN ADVERSE SHOCK



Notes: Shown is the average model response in annualized percentage points to a -3.5 standard deviation demand shock under the Taylor rule with the baseline calibration (Appendix).

Source: Author's calculations

Table 2

ECONOMIC PERFORMANCE IN THE PRESENCE OF THE ZLB

<i>Taylor Rule</i>			
Measurement errors:	Standard deviation (Percent increase)		
	Inflation	Real output gap	
None	0.38	1.23	
Normal	0.56 (47)	1.49 (21)	
Large	0.72 (90)	1.76 (43)	
<i>Growth rule</i>			
Measurement errors:	Standard deviation (Percent increase)		
	Inflation	Real output gap	
None	0.57	1.60	
Normal	0.60 (5)	1.65 (3)	
Large	0.64 (12)	1.72 (8)	

Notes: See notes to Table 1.

Source: Author's calculations

In the presence of the ZLB, the volatility in output and inflation associated with each policy rule depends on the size of the measurement errors. Table 2 shows the following results:

1. Without measurement errors, the Taylor rule leads to less volatility in inflation and the output gap than the growth rule.
2. With measurement errors, volatility rises under both rules. However, it rises by less under the growth rule.
3. With normal measurement errors, under the Taylor rule the volatility of inflation rises 47 percent and the volatility of the output gap rises 21 percent. In contrast, under the growth rule volatility rises only 5 percent for inflation and 3 percent for the output gap. Despite the smaller increase in volatility under the growth rule, volatility is lower under the Taylor rule.
4. With large measurement errors, under the Taylor rule the volatility of inflation rises 90 percent and the volatility of the output gap rises 43 percent. In contrast, under the growth rule volatility rises only 12 percent for inflation and 2 percent for the output gap. Thus, volatility is lower under the growth rule than under the Taylor rule.

When the analysis takes account of the ZLB, the growth rule becomes relatively less effective. A policy that focuses on GDP growth results in a higher incidence of hitting the ZLB. Irrespective of the size of the measurement errors, the policy rate is estimated to fall to zero roughly 16 percent of the time under the growth rule. In contrast, the policy rate falls to zero roughly 8 percent of the time under the Taylor rule.¹⁹ Thus, under the growth rule the policy rate falls to zero 8 quarters more often than under the Taylor rule over a period of 25 years. A higher incidence of hitting the ZLB leads to a higher volatility in output and inflation.

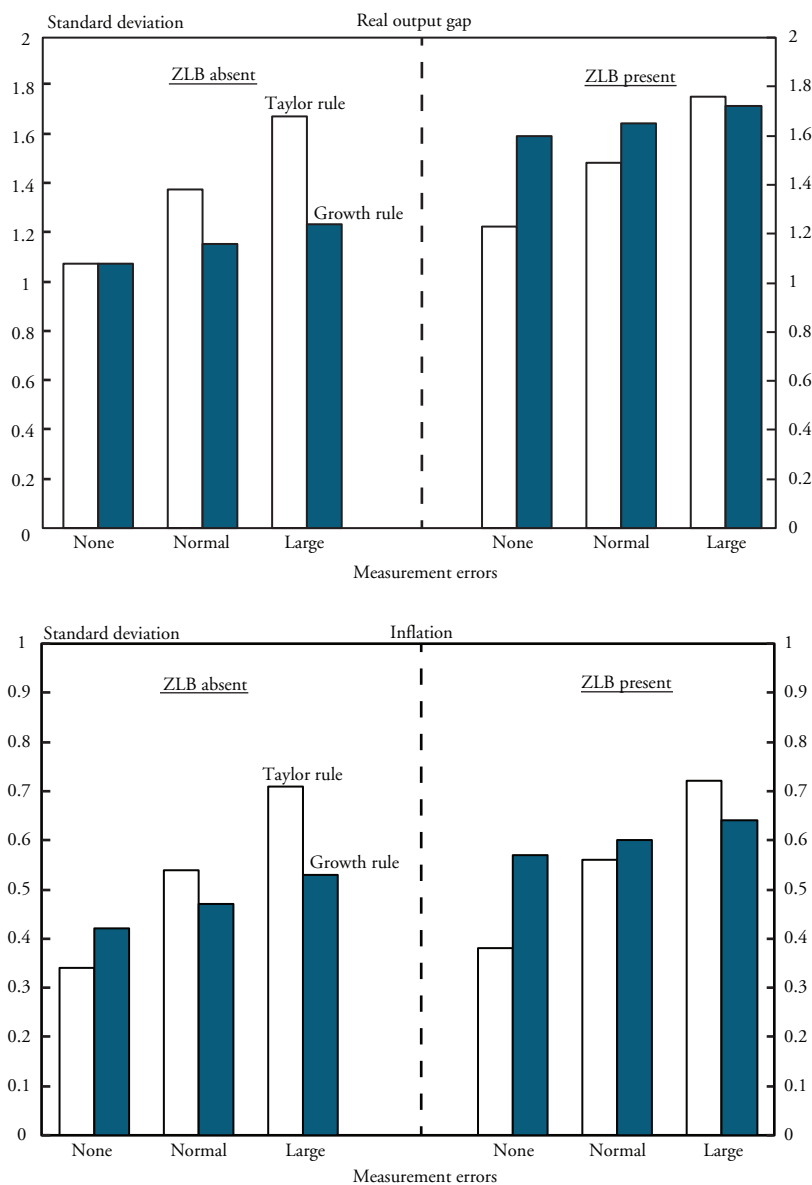
Chart 5 shows the differences that arise when the analysis takes account of the ZLB. The results from Table 1 (without the ZLB) appear on the left side of the chart, while the results from Table 2 (with the ZLB) appear on the right side. On each side, the white bars represent the volatility under the Taylor rule, while the blue bars represent the volatility under the growth rule. Comparing the height of the bars yields the following results:

1. Irrespective of the size of the measurement errors, the presence of the ZLB leads to a higher volatility in the real output gap (top panel) and inflation (bottom panel) under both rules.
2. Without measurement errors, volatility is lower under the Taylor rule with and without the ZLB.
3. With normal measurement errors, volatility is lower under the growth rule in the absence of the ZLB. However, consideration of the ZLB causes volatility to become lower under the Taylor rule.
4. With large measurement errors, volatility is lower under the growth rule with and without the ZLB. However, the increase in volatility due to the ZLB is greater under the growth rule than under the Taylor rule.

In sum, if the analysis fails to account for the ZLB, it overstates the effectiveness of a policy that focuses on GDP growth. Irrespective of the size of the measurement errors, a policy that focuses on the output gap becomes relatively more effective when policy rates are constrained by the ZLB.

Chart 5

ECONOMIC PERFORMANCE AND THE ZLB



Notes: Shown is the standard deviation in annualized percentage points obtained from a standard model calibrated to the U.S. economy (Appendix). The results from Table 1 appear on the left side of the chart, while the results from Table 2 appear on the right side. On each side, the white bars represent the standard deviation under the Taylor rule, while the blue bars represent the standard deviation under the growth rule.

Source: Author's calculations

IV. CONCLUSIONS

A central question in monetary policy analysis is whether policy-makers should focus on the output gap or real GDP growth as an indicator of economic activity to assess economic conditions and set an appropriate stance for monetary policy. While the output gap is a key determinant of the behavior of the private sector and inflation in most macro models, GDP growth is measured in real time with greater accuracy. Researchers who have analyzed this issue found that a policy that focuses on GDP growth can lead to less volatility in output and inflation to the extent that GDP growth gives a more accurate signal of economic activity in real time than the output gap. This line of research, however, has ignored the ZLB by implicitly—and unrealistically—assuming policymakers can set policy rates below zero.

To address this limitation in previous research, this article uses a standard model and takes account of the ZLB. It finds that, in failing to account for the ZLB, previous research overstated the effectiveness of a policy that focuses on GDP growth. While a policy that focuses on GDP growth is more robust to errors in the measurement of economic activity, it also forces policymakers to move the policy rate more vigorously to offset disturbances to aggregate demand, resulting in more frequent encounters with the ZLB. A higher incidence of hitting the ZLB leads to a greater volatility in output and inflation. As a result, a policy that focuses on GDP growth becomes relatively less effective when policy rates are constrained by the ZLB.

APPENDIX—DESCRIPTION OF THE MODEL

This appendix describes the standard model used to compare economic performance under a policy that focuses on the output gap with one that focuses on GDP growth. The appendix provides the equations of the model. It then calibrates the model to the U.S. economy.

Standard economic model

The basic version of the New-Keynesian model embodies three equations to explain the evolution of inflation, real GDP, and interest rates (Galí; Woodford).

The first equation is a *Phillips curve*, which is based on firms' pricing decisions. It takes the form:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa (y_t - y_t^*). \quad (\text{A1})$$

It has two parts. It states that inflation today rises when expectations of inflation tomorrow rise. Inflation also rises when high household consumption pushes real GDP above potential or, in other words, when the real output gap is positive.

The second equation is an *Euler equation*, which is based on households' spending decisions. It takes the form:

$$y_t - y_t^* = E_t (y_{t+1} - y_{t+1}^*) - \varphi (i_t - E_t \pi_{t+1}) + \varphi \eta_t. \quad (\text{A2})$$

It has three parts. It states that household consumption today rises when expectations of consumption tomorrow rise. Household consumption also rises when the real rate of interest falls. And it might rise in response to economic "shocks" that positively affect consumption. Such a shock might derive from numerous factors, such as changes in consumer preferences, productivity, government expenditures, or other temporary factors. The shock, as typical, is assumed to be a first-order autoregressive process, normally distributed.

The third equation is a simple rule, which the central bank uses when setting the policy rate to zero or positive levels, $i_t \geq 0$, in each period t .²⁰ Two rules are considered.

The first rule is the *Taylor rule*, or equation (TR) in the text. For convenience, it is reproduced here:

$$i_t = i^* + \alpha (\pi_t - \pi^*) + \gamma (\tilde{y}_t - \tilde{y}_t^*). \quad (\text{A3})$$

Accordingly, the policy rate is a function of three factors. The first factor is the equilibrium nominal rate of interest, or the equilibrium real rate plus policymakers' long-run inflation goal ($i^* = r^* + \pi^*$). The second factor is the inflation gap, or the deviation of current inflation from the inflation goal. And the third factor is the real-time output gap, or the deviation of real GDP from potential. Denoting the revised output gap as $x_t = y_t - y_t^*$, the real-time gap is equal to the revised gap plus the measurement error, $\tilde{x}_t = x_t + z_t$.

The second rule is a modified version of the Taylor rule, or a growth rule. It is equation (GR) in the text, which for convenience is reproduced here:

$$i_t = i^* + \delta(\pi_t - \pi^*) + \theta(\tilde{g}_t - g^*). \quad (\text{A4})$$

On the right side of this rule, the first two factors are the same as in the Taylor rule. The third factor, however, is the real-time growth gap, or the deviation of real GDP growth from trend, instead of the output gap. Real growth is simply the change in real GDP, $g_t = \Delta y_t$. Real-time growth is equal to revised growth plus the measurement error, $\tilde{g}_t = g_t + v_t$. And trend growth is assumed to be constant and known without error.²¹

Calibration

Table A1 shows the baseline calibration of the model. The values of the parameters of equations (A1) and (A2) are derived from Woodford's table 6.1 based on U.S. data, with two modifications. First, the value of φ represents a lower degree of interest-sensitivity of aggregate expenditure, to not exaggerate the size of the fall in real GDP when the policy rate hits the ZLB. Second, the value of the autoregressive coefficient of the shock η represents a more persistent shock, to make the economic dynamics more persistent.

The values of the parameters of the Taylor rule (A3) are derived from Taylor's proposal. The same values are used for the growth rule (A4), with the exception of the coefficient on the inflation gap, δ . To make the rules comparable, δ was chosen to produce the same output gap volatility under both rules in the absence of the ZLB and measurement error.

Finally, processes for the measurement errors were estimated from fitting the historical revisions shown in Chart 3 with a first-order autoregressive process, normally distributed. Specifically, z was estimated from the output gap revision, while v was estimated from the GDP growth revision.

Table A1
BASELINE CALIBRATION OF THE MODEL

Parameter	Numerical value
β	0.99
κ	0.024
φ	1
r^*	0.5%
π^*	0.5%
α	1.5
γ	0.5
δ	7.0
θ	0.5
g^*	2.5%
$s.d.(\eta)$	0.93%
$s.d.(z)$	1.33%
$s.d.(v)$	0.79%
$AR(1)$ coefficient of η	0.70
$AR(1)$ coefficient of z	0.81
$AR(1)$ coefficient of v	0.79

Note: Because in the model a period is one quarter, the parameter values correspond to inflation and interest rates measured at a quarterly rate.

Sources: Taylor, Woodford, and author’s calculations

ENDNOTES

¹A related issue is that different methods may provide different estimates of potential output (Lubik and Slivinski; Weidner and Williams).

²The staff at the Federal Reserve Board began to compute their own output gap measures in the 1980s. In the 1970s, the measures used in Federal Open Market Committee discussions came from the Council of Economic Advisors (CEA). In 1975, the CEA's measure stood at -15 percentage points. In hindsight, most conventional methods would estimate the depth of the 1975 recession to be much smaller. For example, CBO's revised measure for the period is -4 percentage points.

³Starting in 1991, the CBO director's testimony before the Congressional Budget Committee included estimates of potential output. For this reason, CBO's real-time output gap series starts only in 1991.

⁴The growth rate was calculated as the four-quarter change in the level of real GDP.

⁵From 1991 to 2010, the autocorrelation of the revisions to GDP growth and CBO's output gap was roughly 0.8.

⁶Although the focus of the article is on inaccurate measurements of economic activity, inflation is also measured with error. A prominent example is the deflation "scare" of 2003, which, in hindsight, was overstated (Billi).

⁷Nominal rates can fall below zero, in theory, if money holdings are taxed or financial assets are not freely convertible into cash.

⁸Like potential GDP, the equilibrium nominal rate is unobserved. In this analysis, it is assumed to be constant. In actuality, both of its components may change over time. The equilibrium real rate is determined by factors relevant for the growth of the economy, such as trends of productivity and employment, which are subject to change. Similarly, policymakers may change their inflation goal. As a result, the equilibrium nominal rate may also change over time.

⁹Moreover, good monetary policy typically requires policy rates to rise more than one-for-one with increases in inflation. This requirement is known as the *Taylor principle*. It ensures the real rate rises when inflation rises above the goal and, therefore, policy leans against inflationary pressures. According to a number of theories and historical analysis, failure to meet the Taylor principle could allow inflation to become unanchored from the goal.

¹⁰Since the sum of inflation and real GDP growth is simply the growth of nominal income, this strategy is closely related to *nominal income growth targeting* (Orphanides, 2003; Rudebusch). An argument against the latter strategy, however, is that the timing of the effects of monetary policy on inflation and output are quite different, with monetary policy affecting inflation with a longer lag. Because it allows policymakers to react differently to inflation and real GDP growth, the growth rule may be a more-effective strategy.

¹¹Trend growth is also subject to measurement error, which is ignored in this analysis.

¹²CBO's output gap estimates are based on the production-function approach. In this approach, the output gap is defined as the deviation of GDP from the level consistent with current technologies and normal utilization of capital and labor. In the New-Keynesian model, the output gap has a more explicit focus on microeconomic foundations.

¹³Searching for the *efficient* coefficients, which minimize a weighted sum of output volatility and inflation volatility, is outside the scope of the article. To make the growth rule comparable to the Taylor rule, the article uses the simpler approach of searching only for the coefficient on the inflation gap in the growth rule. In the standard model, increasing this coefficient reduces volatility in both inflation and output, which, in turn, may lead to less volatility in the policy rate. Increasing the coefficient on the inflation gap in the growth rule to 7.0 was found to reduce volatility in the policy rate and produce the same output gap volatility as under the Taylor rule in the absence of the ZLB and measurement error.

Two other approaches were also considered. In one, the coefficient on the inflation gap in the growth rule was further increased to 11.0, producing the same output gap volatility under both rules in the absence of measurement error when the analysis takes account of the ZLB. The results are qualitatively the same, with the Taylor rule becoming relatively more effective when policy rates are constrained by the ZLB. But such an approach gives the false impression that the growth rule is more effective in the absence of the ZLB and measurement error. In another approach, the coefficient on the inflation gap in the growth rule was allowed to be different in the absence or presence of the ZLB (7.0 and 11.0, respectively). Because this implies that policymakers can re-optimize the growth rule to account for the ZLB, such an approach overstates the effectiveness of the growth rule. As a result, both approaches fail to give a "fair" comparison of the rules.

¹⁴The analysis assumes that the *aggregate* private sector—the sum of all households and firms in the economy—possesses full information about the state of the economy in real time. This implies that the model can be treated as structurally invariant under different policies (Aoki; Svensson and Woodford).

¹⁵A standard, first-order autoregressive process describes quite well the historical revisions.

¹⁶The persistence of the measurement errors is almost the same for the two indicators, but this does not matter for the result. What drives the result is that the volatility of the measurement errors is smaller for GDP growth.

¹⁷This occurs, in typical macro models, because the behavior of the private sector and inflation depends crucially on the output gap. As a result, all else equal, a policy that ignores the output gap and focuses on GDP growth is relatively less effective.

¹⁸Shown is the average model response in annualized percentage points to a -3.5 standard deviation demand shock under the Taylor rule with the baseline calibration (Appendix).

¹⁹Under both rules, measurement error may lead to a higher incidence of hitting the ZLB. Even with large measurement error, however, the incidence of hitting the ZLB rises by less than 1 percent.

²⁰To account for the ZLB, the model was solved using a global numerical procedure. The procedure adds a bias term to the *notional* inflation goal to ensure that, on average, inflation reaches the goal.

²¹It follows that the revised growth gap is simply the change in the revised output gap.

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